A NOVEL TECHNOLOGY FOR DETERMINING STRENGTH AND REDUCE CLIMATE-GAS EMISSIONS IN DEEP SOIL MIXED PILES

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KEYWORDS

Deep-soil mixing, Laboratory procedure, In-situ testing, Seismic, Temperature, Sustainability

ABSTRACT

A new non-destructive methodology for documentation and prediction of strength in binder-stabilised piles is developed. The methodology comprises improved laboratory procedures, continuous in-situ temperature monitoring and cross-hole seismics that may be conducted at any time and repeated in the same pile during the curing process. By applying this methodology, climate-gas emissions may be reduced by more than 39% and costs by more than 16%.

1. EXAMPLE INTRODUCTION

Today, the strength of deep-dry mixed piles (DDM piles) is documented by in-situ tests such as reversed pile soundings (RPS), (predrilled) lime-pile soundings (FKPS) or cone penetration tests (CPTU). Due to practical limitations of these tests, they are often conducted during the first week after installation of the piles. However, the curing and the strength increase continues over a much longer period. This larger strength is not included in the design

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of the piles, thus causing unnecessary excess consumption of binders, and large climate-gas emissions.

The innovation project KlimaGrunn (2018-2023) [1] have developed a new non-destructive procedure for documentation and prediction of strength in DDM piles that may be conducted at any time and repeated in the same pile during the curing process. The procedure is developed combining concrete technology, geotechnical engineering, sensor technology and geophysics.

The KlimaGrunn methodology [1] involves the whole process of deep mixing, from the initial site investigations, preparation and testing of laboratory-mixed specimens, how the results are used in design, and monitoring and testing in the construction phase. A new laboratory procedure for moulding and curing laboratory specimens is developed improving the correlation between the strength determined in the laboratory and in situ. Laboratory results form the basis for correlation models developed for prediction of strength development over time. During the construction phase, the temperature is continuously monitored by sensors installed at various levels in the piles. The temperature is used for estimating the strength of the piles based on the correlation models and is also used for updating the predicted curing time in-situ. Cross-hole seismics are conducted repeatedly in the same pile and documents the as-built strength and homogeneity over the whole depth of the piles.

This paper describes KlimaGrunns methodology, also presenting results from field experiments carried out in the Oslo region [1], and from two sites in Østfold and Nordland, Norway.

2. THE KLIMAGRUNN METHODOLOGY

Site investigations

The obtained strength of the DDM piles is influenced by the in-situ material properties (i.e. grain-size distribution, water content, density, remoulded shear strength, plasticity index). Therefore, it is necessary to map the variations over the site where DDM is planned, and to collect enough soil from each representative soil layer for moulding laboratory specimens to quantify the effect of binders (preferably various amounts, types and combinations). The extracted soil samples are sealed and stored at 6-8 °C at 100% humidity. Storage time should be kept at a minimum to avoid any chemical alteration or loss of water. Due to loss of material during the mixing and preparation of the specimens, about 600-700 g (about 13-18 cm of a 54-mm piston sample) of soil is needed to prepare one specimen.

KlimaGrunns laboratory procedure

The strength in binder mixed laboratory specimens is affected by the density [2], [3]. In situ, the binders are blown into the soil with an air pressure and mixed with the soil creating a heterogenous matrix with air-filled voids. It is therefore not possible to predict what density is achieved in the piles in-situ, and there is not much data available documenting the density of DDM soils. Compared to in-situ density of non-stabilised soils, Falle [2] reports less than 4% reduction of the density in samples collected from DDM piles mixed with 30, 50 and 80 kg/m^3 binders and cured for 9 weeks. Multiconsult [4], [5], report less than 6% reduction in piles with 90-100 kg/m^3 binders cured for 25 weeks. To avoid overestimating the strength, it is therefore recommended to mould the specimens to a target density 5% lower than the density of the original, non-stabilised soil.

A new equipment was developed allowing preparation of specimens with the intended target density having a height of 100 mm and diameter of 54 mm maintaining constant volume during curing (Figure 1). The equipment consists of:

- A 180-mm high cylinder with an inner diameter of 54 mm (Figure 1a).
- Two distance pieces with 1-2 mm holes (vents) in the centre is used for compressing the specimens to a final height of 100 mm (H/D ratio of 1,85) (Figure 1a).
- A hand-held rod with structured surface (waffle pattern or similar).
- A 10-20 mm high split ring mounted at the bottom distance piece (Figure 1a and b). When removed this allows for compression of the specimens from both ends (Figure 1c). Moist paper filters placed at the top and bottom of the specimen inhibit material from the specimen to be squeezed out through the vents.
- 180-mm long extruder rod (Figure 1**Error! Reference source not found.**a).

To ensure comparable results, enough soil from the same representative layer to mould all the specimens (all binder combinations and curing times) should be homogenised simultaneously. Preferably, three (minimum two) specimens with the same soil, binder combination and curing time are moulded. As a minimum three specimens of same type are cured for 28 days, but it is recommended to produce several sets of specimens with different curing times (i.e. 7 and 90 days).

The specimens are moulded by splitting the binder-mixed mass into minimum four parts of equal weight. These parts are filled into the cylinder using the muddler whilst minimising the size of air-filled voids. To avoid defined layers in the specimen, each layer should have an uneven surface prior to filling in the new layer. To make sure that the mass is evenly distributed over the height of the specimen, the first two layers are compressed with the muddler so that they have a height of 5,1-5,5 cm. Thereafter layers no. 3 and 4 are filled into the cylinder to a total height of 10,1-10,5 cm. The unconfined compression

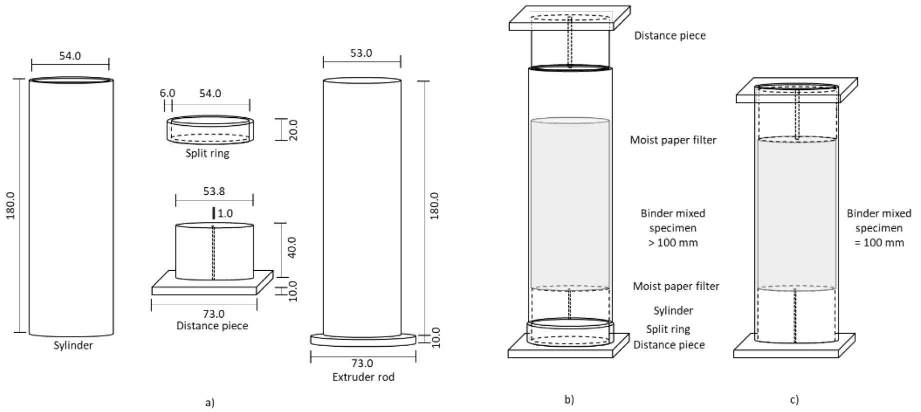

Figure 1 Sketch of a) equipment, b) moulded specimen prior to removal of the split ring and final compression in the unconfined compression apparatus and c) after final compression and ready for curing.

apparatus is used for pressing both the top and bottom pieces into the cylinder until they fluctuate with the cylinder walls. The specimens are stored vertically at 20 ± 2 °C and 100% humidity until extrusion and testing. The temperature in the storage room must be documented.

After curing, the shear wave velocity is measured by bender element (BE) tests prior to unconfined compression (UC) tests (σ_3 = 0 kPa) on the same specimens applying a strain rate of 1.5%/min. The undrained shear strength ($c_{u,UC}$) is calculated as half the unconfined compressive strength (q_u) [6].

Correlation models

The quality of the laboratory results may influence the correlation models and must therefore be evaluated, and deviating results must be filtered out from the input data such as:

- Ratios of height to diameter (H/D) deviating from 1.8-2.1.
- Large deviations from target density of the cured specimens (> 5 %)
- Deviating water content of the homogenised soil compared to in-situ water content, and large internal deviations in the water content amongst cured specimens of the same type.
- Poorly prepared specimens (i.e. horizontal layering/cracks, large volumes of air-filled pockets).
- Deviating stress-strain curves, and large internal deviations of the obtained shear strength (> 15 % from median $c_{u,UC}$) and shear wave velocity (V_s) amongst three specimens of the same type.

The curing time in the laboratory at 20 ± 2 °C (t_{eq}) is not the same as the in-situ curing time in the piles (t_c) where the temperature varies over time (Figure 2). Therefore, the laboratory-based correlation model for the development

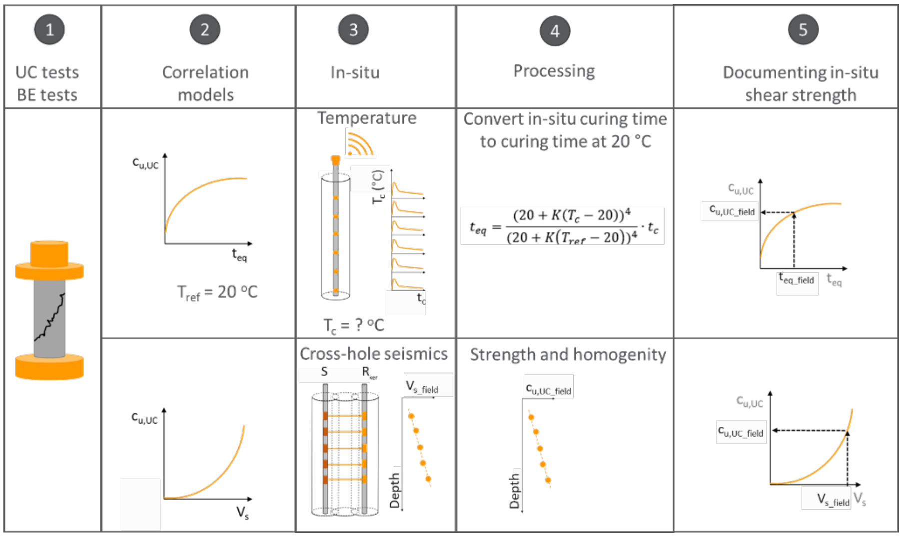

Figure 2 Combining laboratory-based correlation models to in-situ measurements of temperature and cross-hole seismics. S = source, R = receiver.

of shear strength over time does not correspond to t_c. The development of temperature in the piles depends on several factors such as installation grid (degree of coverage), binder type and quantity and the clay's thermal material properties [7], [8], [9], [10], [11], [12].

The temperature in the subsurface in Norway is around 6-8 °C. Exothermal chemical reactions between binders and soils start immediately after mixing. A rapid increase of the temperature is observed in the piles in the days following installation. The temperature is higher than in the surrounding soil and remains elevated for days, weeks or months after installation [7], [11], [12], [13], [14]. Therefore, it is recommended to cure the laboratory specimens at a higher curing temperature than the in-situ soil temperature [15]. Ideally the curing temperature should be as in the piles which, however, is hard to obtain in the laboratory.

In concrete technology specimens are cured at 20 ± 2 °C, which is also recommended by [16]. The maturity number is used in concrete technology to be able to compare the progress of curing for concrete samples with different temperature histories. A principle also adapted for binder-stabilised soils (Equation 1) [7].

$$M(T_c, t_c) = (20 + K(T_c - 20))^2 \cdot \sqrt{t_c} \qquad \text{Equation 1}$$

Where M is the maturity number (degree-days), T_c is the in-situ curing temperature (°C), t_c is the in-situ curing time after installation (days), and K is a constant varying with soil and binder types. A K of 0.5 is applied for Swedish clays and silty clays [7] and is considered applicable also for Norwegian clays and silty clays. By curing the laboratory specimens at a reference temperature of 20 °C (T_{ref}), Equation 2 is derived from Equation 1 for estimating how long it will take for piles cured at any temperatures to obtain the same curing time as if they were cured at constant 20 °C, referred to as the equivalent curing time (t_{eq}). For instance, at constant 7 °C the pile must cure for 135 days to obtain the same M as a representative specimen cured at 20 °C for 28 days.

$$t_{eq} = \sum \frac{(20 + K(T_c - 20))^4}{(20 + K(T_{ref} - 20))^4} \cdot \Delta t_c \qquad \text{Equation 2}$$

This means that regardless of the temperature history in the pile, temperature measurements in situ can be used for calculating the equivalent curing time at 20 °C (t_{eq_field} in Figure 2), and thereby relate the progress of curing in situ to the strength measured on laboratory specimens cured at 20 °C (c_{uUC_field} in Figure 2).

In Åhnberg's correlation model [17], the undrained shear strength ($c_{u,UC}$) is normalised by the average of the shear strength obtained after 28 days of curing ($c_{u,UC28}$) (Equation 3). This correlation model creates in most cases a conservative, lower boundary for the data produced by applying KlimaGrunns laboratory procedure on soils from Eastern and Northern Norway mixed with various types and amounts of binders. Åhnberg's correlation model is modified by replacing t_c with t_{eq} in Equation 3. In most of the results, a higher shear strength than what appears from the correlation model is developed after a short curing time (Figure 3a). In such cases, a correlation model for the local site conditions may be more appropriate as suggested by the second function in Figure 3a which have a higher rate of strength increase during the first part of curing, but slightly slower than Åhnberg's correlation model after 28 days.

$$\frac{c_{u,UC}}{c_{u,UC28}} = 0.3 \cdot \ln(t_{eq}) \text{ modified after [17]} \qquad \text{Equation 3}$$

In general, there is a scatter in the shear wave velocity interpreted from the bender-element tests (Figure 3b). Nevertheless, Dannewitz et al. [18] correlation model in Equation 4 fits well with a rough average of the results in the scatter. Developing locally fitted correlation models may be necessary, such as the upper and lower limits suggested in Figure 3b. In situ, the shear strength estimated based on temperature may be verified by shear-wave velocities interpreted from cross hole seismics (Figure 2).

$$c_{u,UC} = 0.0424 \cdot V_s^{1.462} \quad [18] \qquad \text{Equation 4}$$

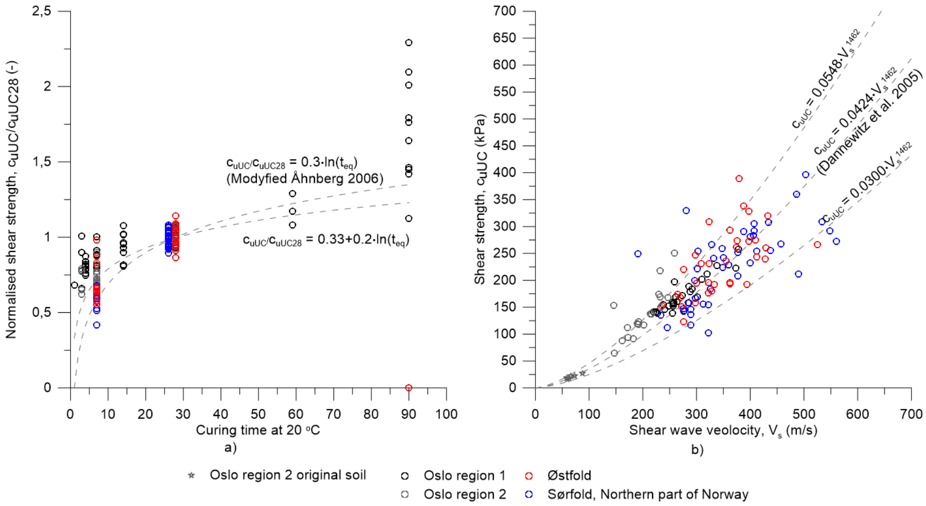

Figure 3 a) Normalised shear strength versus curing time at 20 °C. b) Shear wave velocity versus shear strength.

In-situ monitoring

The complexity of the site conditions over the area where DDM is planned influences the set-up of the monitoring. To capture temperature variations over the site and differences this may cause in the rate of strength increase, it is recommended to monitor all variations of installation grids, pile diameters, binder combinations and soil types over the site. Furthermore, instruments should be installed in the outskirts as well as in the central parts of the ground-improved areas.

To ensure contact between the DDM soil and instruments, temperature sensors and casings for cross-hole seismics are installed directly after installation

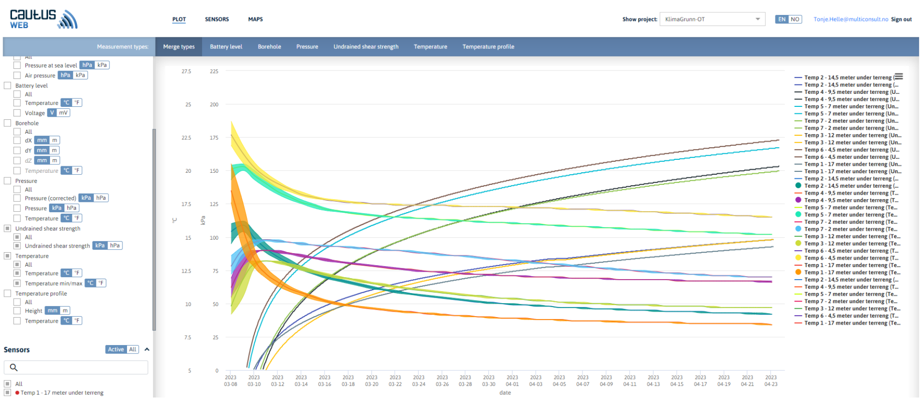

Figure 4 Temperature and strength development over time at various depths in the monitored pile as presented at Cautus Web (https://cautusgeo.com/cautus-web/).

of the piles. It is recommended to install temperature sensors at multiple levels in the piles (Figure 2a). Preferably a minimum of four sensors over sections of 10 m length, starting at around 3 m depth down to half-a-meter above the end of the pile. The data are automatically transferred to the cloud and presented live at Cautus Web (Figure 4).

The correlation for shear strength development based on temperature and curing time in Equation 3 is considered conservative. In-situ the piles cure under overburden stress, thus most likely obtaining higher shear strengths than determined from the UC tests. The shear wave velocity increases with increasing shear strength (Figure 5). Thus, the effect of overburden stresses on obtained shear strength may be detected by cross-hole seismics (Figure 6).

Cross-hole seismics are conducted between casings installed with a minimum distance of 2 m in panels with overlapping piles. To ensure that the shear wave velocity is calculated correctly, the distance between the two casings at any depths are documented by inclinometer measurements. Waves are transmitted from a source (S) in one casing and received by a receiver (R) positioned at the same level in the other casing (Figure 2b). It is recommended to apply a receiver that registers particle movements in two horizontal directions in the S-R plane allowing the source to be rotated 180 degrees to obtain polarised shear waves in the horizontal direction for easier detection of the first arrival of shear waves. The data are processed by filtering of frequency (keep

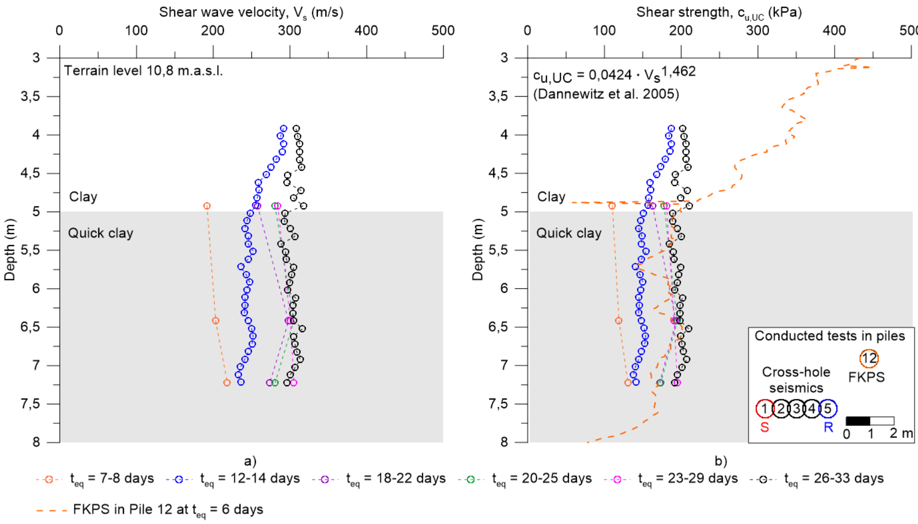

Figure 5 a) Interpreted shear wave velocity measured at several points after installation, and b) corresponding shear strength calculated by Dannewitz et al. (2005), and also compared to interpreted shear strength from conducted FKPS in nearby single pile no. 12 at equivalent time at 20 °C of 6 days. The cross-hole seismics is conducted with the source in pile no. 1 and the receiver in pile no. 5. The clay is mixed with 80 kg/m³ 50/50 ByPass Dust (BPD) and CEM II.

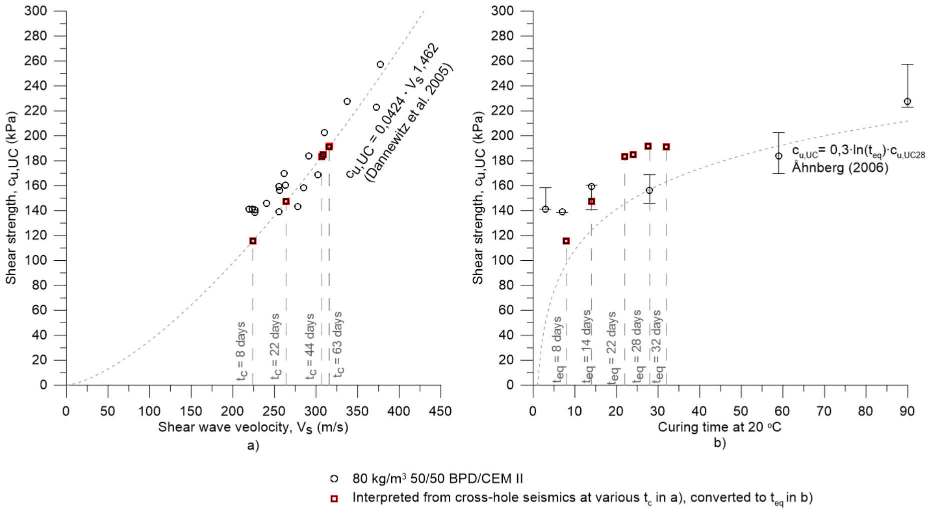

Figure 6 a) Interpreted shear wave velocity measured by cross-hole seismics (red symbols) several times after installation and b) plotted against shear strength over equivalent time at 20 °C. The clay is mixed with 80 kg/m³ 50/50 BPD/CEM II.

ing 30-300 Hz), subtraction of signals from the opposite directions and analysing of the first arrival.

As a minimum cross-hole seismics should be carried out at the same levels as the installed temperature sensors early in the curing process to verify the laboratory-based correlation model, and for example at every 10 cm to document the as-built strength and homogeneity of the piles prior to construction work (Figure 5). Shear strength interpreted from cross-hole seismics is in the case shown in Figure 5b considered to be conservative compared to conventional FKPS carried out in a nearby single pile.

Data presentation and documentation

All registered users can follow the strength development live during the construction phase via the web application Cautus Web. The temperature measurements are updated continuously, and the equivalent time (t_{eq}) is automatically calculated by applying Equation 2. The strength increase is documented by the laboratory-based correlation model (i.e. Equation 3), shown both with the in-situ curing time and equivalent time at 20 °C. It is also possible to add predictions of how the strength will continue to develop over time. In addition, the data from cross-hole seismics are presented together with the inclinometer measurements.

3. REDUCED CLIMATE-GAS EMISSIONS AND COSTS

In the following, results from KlimaGrunns site experiment at E18 Vestkorridoren is used in a simplified example to estimate the potential for reducing climate-gas emissions and costs by applying KlimaGrunn's methodology. The calculations are based on 15 m long 800 mm piles installed with a 150 mm overlap in a 20 m long panel of single piles over an area of 100 x 20 m. The piles must obtain a minimum shear strength of 100 kPa, and the average shear strength of the stabilised soil volume must in this case be of 60 kPa minimum.

Until recently it has been common to apply binder quantities of 80-110 kg/m^3. However, laboratory tests on quick clay from E18 Vestkorridoren showed that it is possible to obtain sufficient shear strength by only adding 45 kg/m^3 (Figure 7a) when allowing the specimens to cure for about 48 days at 20 °C. By applying 80 kg/m^3 sufficient shear strength is obtained during the first week of curing, and a strength of 160 kPa is obtained in specimens by curing for 48 days at 20 °C. There are only minor differences between binders containing CL80/CEM I (lime and cement) and BPD/CEM II (ByPass Dust and cement with fly ash). BPD/CEM II with a smaller climate footprint is therefore considered in the following.

By allowing the 80 kg/m^3 cure for 48 days, the centre distance between the panels may be increased and thereby reduce the total number of piles over the ground-improved area (Alternative A in Figure 7a), and thereby reduce the climate-gas emissions and costs by 39%. By keeping the number of piles and rather decrease the binder quantity from 80 to 45 kg/m^3 in the piles (Alternative B in Figure 7a), the climate-gas emissions are reduced by 44% and the costs by 16%. Be aware that the climate-gas emissions only include the production of binders and not the fuel consumption during installation and

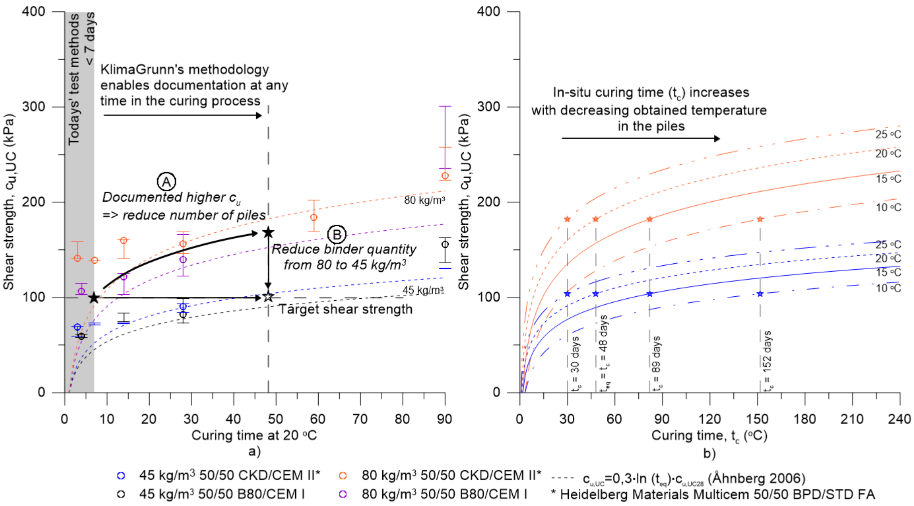

Figure 7 a) Increased curing time allows for reduced climate-gas emissions applying Alternative A or B. b) In-situ curing times (t_c) to obtain target shear strength differs from the laboratory curing time at 20 °C, depending on in-situ temperature in the piles.

transport. How quickly the target shear strength is obtained depends on how the temperature develops in the piles in situ Figure 7b).

4. CONCLUSIONS AND FURTHER WORK

By applying KlimaGrunn's methodology the binder combination is optimised for local site conditions and design criteria facilitating reduction of both climate-gas emissions and costs. Furthermore, the continuous monitoring and live presentation increases the control of how the strength in the piles develops in the construction phase improving the safety prior to commencing of construction work. The live-updated correlation models may be used actively in the progress planning. Cross-hole seismics may also be used for documentation of the durability of existing piles. Although the method may seem time consuming and expensive, this will pay off as a result of reduced number of piles and/or binder quantities and increased control in the construction phase.

A public database should be established so that correlation models for soils of varying grain-size distributions and properties may be developed to make it easier to optimise the binder combinations for local site conditions without the necessity of large number of laboratory tests.

Laboratory studies show promising results in reducing the binder content and still obtain sufficient strength. However, today's drill rigs may limit how well the binder and soil is mixed when the added quantity of binders decreases below 22.5 kg/m (i.e. 45 kg/m^3 for a 800 mm pile and 60 kg/m^3 for a 600 mm pile). Therefore, contractors are encouraged to develop rigs with mixing tools that may improve the homogeneity of the piles, and also documenting the installed position.

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